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Review of Soviet/Russian Literature on Residual Stress Development in Filament-Wound Polymer-Matrix Composites

by Eric D. Wetzel and Scott R. White

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14. ABSTRACT

This report provides a review of select Soviet and Russian (S/R) literature, from the mid 1960s to the mid 1990s, related to residual stresses in wound composite articles. Through a compilation of S/R review articles, a historical overview of the development of this S/R knowledge base is first provided. This overview is then followed by detailed compilations of the following topics: experimental measurement of residual stress development in wound composites, cure shrinkage in neat polymers, residual microstress development, modeling residual macrostress development, and manufacturing methods for controlling residual macrostresses in wound composites. This study, though not a comprehensive review of S/R residual stress literature, provides a general survey which should prove useful for identifying published sources of S/R technical expertise.

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1. Background

1.1 Objective

In the 1990s, the U.K. Ministry of Defence, Defence Evaluation and Research Agency ([DERA], which has since split into a U.K. Ministry of Defence office, Defence Science and Technology Laboratory, and a private company [QinetiQ]) contracted a Russian university professor, Zlinksy, to propose a model for residual stress development in wound, polymer-matrix composites.* As part of this proposal (*1*), Zlinsky provided a survey of Soviet and Russian literature related to the development of residual stresses in polymer matrix composites, with specific emphasis on thick-section filament-wound components. A majority of the referenced Soviet/Russian articles were subsequently collected by DERA.

This report will examine these collected articles in more depth, and highlight some of the most significant results. Little attempt is made to critique or editorialize the results, or to synthesize the information into larger conclusions. Instead, this review should be considered a starting point for identifying veins of Soviet/Russian literature which could be relevant to existing research efforts.

1.2 General Summary of Residual Stress Development in Wound Composites

Before presenting the full review, it is useful to summarize the physical processes which lead to the development of residual stresses in composite articles. We will focus on filament-wound composites, since they are the focus of most of the reviewed articles.

We will first define "residual stresses" as those stresses not caused by the external application of mechanical forces. We will use this terminology for both the stresses formed during processing, and those left in the part once processing is complete. In some cases we will use the term "processing stresses" to specify residual stresses which are formed during processing, and which may or may not persist once processing is complete.

Filament winding involves winding a tensioned tow of reinforcing fibers around a rotating mandrel. The fibers are typically pulled through a resin bath before reaching the mandrel, or resin is applied manually to the part as winding progresses. The angle of winding is designed to achieve specific mechanical properties in the final part, and may be varied over the thickness or length of the part. Once winding is complete, the part is heated to complete the cure reaction in the resin. The cured composite is then cooled to room temperature, and removed from the mandrel.

* Unfortunately, no further details are available on the full name or location of Prof. Zlinsky, or on the agreement under which this study was performed for the Defence Evaluation and Research Agency of the U.K. Ministry of Defence.

A variety of component flaws or deficiencies can be formed during the fabrication process, many of which are due to process stresses during production or residual stresses remaining after processing is complete. These problems include:

- Interlaminar failure: hoop-oriented cracks in the structure.
- Macroscopic voids: voids, in the polymer matrix, whose size is comparable to the part thickness.
- Microscopic voids: voids, in the polymer matrix, whose size is comparable to the fiber diameter.
- Wrinkles: waviness in the fibers which remains after the matrix is fully cured.
- Springback: elastic strain of the component after it is removed from the mandrel, often to a shape which is different from the intended component geometry.
- Reduction in effective failure strength: residual stresses in the part preload the material, reducing the external loads that can be applied before inducing material failure.

The study of residual stress development in composites is largely aimed at understanding the sources of these problems, and discovering ways to prevent their formation during processing.

Residual stresses are often categorized as either macrostresses or microstresses. Macrostresses are residual stresses which vary at a length scale comparable to the part thickness. These stresses are typically ply-level stresses, and result in such failures as interlaminar cracking. Microstresses are residual stresses which vary at a length scale comparable to the fiber diameter. These stresses are typically due to the differences in the thermal expansion coefficients of the polymer phase as compared to the fiber phase and, if sufficiently large, can cause failure of the fiber-to-matrix bond.

Residual stresses are largely due to the combined effect of chemical and thermal strains. Chemical strains refer to the dimensional changes (typically shrinkage or density increase) of the matrix phase which takes place as the polymer cures. The overall magnitude of chemical strains can be quite large, but does not always lead to residual stress due to stress relaxation of the polymer. This stress relaxation is especially fast while the matrix is not fully cured, behaving like a viscoelastic fluid, but can even take place in the fully cured polymer at elevated temperatures.

Thermal strains refer to dimensional changes driven by the coefficients of thermal expansion (CTEs) of a material. In an unconstrained isotropic material, thermal strains do not produce residual stresses. However, composites are almost always anisotropic, and when heated or cooled from a stress-free state this anisotropy leads to nonuniform thermal shrinkage, which produces residual stresses. Since polymer composites are typically cured in a stress-free state at high temperatures, cooling to room temperature introduces residual stresses which persist during

the service life of the part. Like chemical stresses, thermal stresses can sometimes be relaxed out during the cooling process by viscoelastic mechanisms.

Flaws such as delaminations, voids, and wrinkles are formed when the instantaneous residual or process stresses exceed the instantaneous failure strength of the material. For example, as the component is cooled, the radial tensile stresses may exceed the radial tensile strength of the material, causing an interlaminar crack. Note that the interlaminar tensile strength of the composite may decrease significantly with increasing temperature, so that failure is often likely to occur at elevated temperatures and persist to room temperature. Flaw formation can also occur before the resin is fully cured. Chemical shrinkage effects have been shown to produce voids in the ungelled, viscoelastic polymer, which remain after cure is complete. Wrinkling typically occurs when residual radial stresses or shear stresses within the partially cured composite are accommodated by material flow, rather than void or crack formation. These wrinkles are fixed in place by the subsequent cure of the polymer matrix.

1.3 Organization of This Report

This review is organized as follows. Section 2 summarizes general review articles related to residual stress development in composites. Section 3 discusses the direct measurement of residual stress levels in composites. Section 4 addresses cure, shrinkage, and flaw development in neat polymers. Section 5 covers thermal and chemical microstresses in composites. Section 6 reviews models of residual macrostress development. Section 7 discusses means of controlling residual stress levels through process and material modifications. For completeness, section 8 lists articles which were included with the original Soviet/Russian survey, but were not included in this review due to relevance or lack of a translated version.

2. Review Articles

A number of Soviet review articles exist which summarize aspects of residual stress development in composite parts. These articles provide a good starting point for understanding general scientific and technical expertise at the time the article was published. The year of publication for each review is noted with each reference, in order to place the reviewed results within the proper historical context.

Sarabeev et al. (*2*) propose standard terminology for residual stresses, in order to eliminate confusion between research groups. They define “residual stresses” as those stresses which persist when their “cause for existence” is removed. “Temporal stresses” are those stresses which disappear as soon as their driving source is removed. They also argue that all stresses are “internal stresses,” rendering this term meaningless and not equivalent to “residual stresses.”

Sarabeev et al. also define macrostresses, microstresses, and submicrostresses. Macrostresses are defined as stresses which are uniform over length scales comparable to the part dimensions, and are typically caused by chemical shrinkage or gradients in CTEs. Microstresses are defined as stresses at the fiber/matrix interface, caused primarily by the differences in CTE between the fiber and matrix phase. Submicrostresses are defined as stresses within the polymer phase itself, which they attribute to differences in the "structural inversions" within the material. They may be referring to molecular orientation effects.

Bolotin (*3*) provides a review of residual stresses, primarily with respect to wound composites. The article begins by discussing some general behaviors of filament wound composites. For macrostresses, radial stresses are the most critical residual stresses, due to the relatively low interlaminar strength of composites. For composites wound under relatively low tension, residual stresses are well predicted using simple elastic models of thermal stresses. Radial residual stresses are necessarily zero at the inner and outer wall surfaces, and tensile within the wall. Hoop stresses are compressive at the outer wall surface, and tensile at the inner wall surface. For hollow cylinders wound under high tension, the residual-stress state is primarily determined by the winding tension, although the effect is not easy to predict using existing models. The viscoelastic properties of the resin are important in determining final residual-stress state, but their effect is only poorly understood. This shortcoming is mainly due to the lack of good experimental data on the viscoelastic properties of resin systems as a function of temperature and degree of cure.

Bolotin also discusses methods of controlling residual stress state. One approach is to vary winding tension. Winding on a hot mandrel also helps to minimize thermal stresses, by eliminating the tensioning effect of an expanding mandrel during the heating to the final cure temperature. The relaxation properties of the resin system can be used to reduce final residual-stress state by cooling the cured composite to just above the glass transition temperature (T_g) of the polymer, and then holding the part at that temperature until the thermal stresses relax out. This approach sets the stress-free state at a relatively low temperature, so that the total thermal stresses upon cooling to room temperature are minimized.

Vinogradov (*4*) provides an extensive review of the technical issues associated with residual stresses in composites. This article is focused on qualitative information and, based on the relatively small number of references, the author's personal experience with composites. The review is not focused on wound composites, as it includes references to molding, stamping, and machining variously reinforced plastics.

Vinogradov provides an especially exhaustive listing of experimental methods for measuring residual stress levels in composites. The methods can be divided into two categories: methods which measure deformations associated with residual stresses, and methods which measure material changes associated with residual stresses.

Deformation-based methods include the following approaches. In the lacquer coating method, a thin brittle coating is applied to a heated, cured part, which is then cooled to room temperature. When the surface strain exceeds a critical value, brittle failure of the coating occurs. The pattern of cracks in the coating helps to determine the distribution of residual stresses at the surface of the part. The mechanical properties of the lacquer can be tailored to match the desired stress levels.

In the relaxation method, a part's dimensions are measured at room temperature. The part is then heated to a high temperature, and held at that temperature long enough for the residual stresses to relax out. The part is then cooled to room temperature, and the dimensions remeasured. The change in dimensions reveals information about the original stress state of the part. This method can be modified by painting an orthogonal grid or Moire pattern on the surface prior to heat treatment.

Mechanical methods typically involve sectioning a part, and then removing or cutting a small piece of the section and observing the resulting mechanical deformation. Well-established protocols for this approach exist for rods, sheets, tubes, discs, etc. This approach is called the Davidenkov method by other authors. A different approach involves mounting strain gages on one surface of the part, and then removing the plies from the opposite surface one at a time. The strain response as a function of ply removal can be used to calculate the ply-by-ply residual stress levels in the part. This approach is called the Sachs method by other authors.

Another approach, more applicable to coatings and adhesives, is the flexible beam method. A thin layer of the coating under investigation is painted onto a flexible beam. The coating is then cured, and the resulting beam deformation is measured. This deformation can be used to calculate the shrinkage of the coating.

A material change-based method of residual stress measurement includes a few approaches. In the active media method, a chemical or fluid is applied to the polymer surface which weakens or embrittles the polymer. The areas with significant residual stress will then crack or spall, with the pattern of damage providing information on the residual stress profile along the surface.

Birefringence (also called photoelasticity) can be utilized to measure three-dimensional (3-D) residual stress levels in polymers. The part must be translucent, although, in some cases, the application of surface layers or filler can also be used. Under illumination from a monochromatic light source, birefringent bands will form in the material, which can be related to the stress state in the material.

Infrared (IR) spectrometry has also been shown to be effective for measuring residual stress levels in neat polymers. In some polymers, application of stress provides enough variation in internal chain conformation to cause a measurable peak shift in the IR spectrum. An advantage of this approach is that spot sizes as small as 40 μm can be used, so that very fine stress field spatial resolution is possible.

Vinogradov also provides a list of methods for reducing residual stress levels in composites. These methods include: preheating the tool; cooling the part as slowly as possible; stress relaxation through thermal annealing; cooling the part under mechanical pressure; minimizing thermal gradients by adding thermally conductive filler to the polymer, or using a volumetric heating approach such as induction heating; reducing the polymer CTE through the addition of filler; reducing polymer crystallization gradients by adding artificial nucleation sites (probably fine filler particles); and adding low-stiffness, elastic interplies within the composite.

Obraztsov and Tomashevskii (*5*) provide a general review of process modeling and the effect of processing on properties of composite materials. The report is largely focused on modeling efforts, and can be roughly organized into the following areas: heat transfer modeling; kinetics and cure modeling; solving the combined heat transfer and cure problem; modeling polymer flow effects; and modeling composite mechanical properties during cure and cooling.

Solution of the heat transfer problem, in most cases, is fairly straightforward. The authors point out that the nature of the thermal gradients in most composites processing leads directly to frontal solidification (see section 4.2).

The cure kinetics can be divided into five stages: (1) heating the uncured resin to the cure temperature; (2) curing the resin; (3) cooling the cured polymer to the T_g; (4) cooling through the T_g; and (5) further cooling to room temperature. During the first stage, viscosity drops exponentially with temperature. During the second stage, cure kinetics are modeled based on the results of DSC experiments. It is during this stage that the elastic properties of the polymer develop. During the third stage, the translation says that the "viscosity decreases with temperature" but the proper translation is probably that viscous and relaxation properties become less important as the polymer cools. During the fourth stage, there is a sudden increase in stiffness as the polymer is cooled through the T_g. This transition is often best modeled using a frontal approach. During the last stage, the material properties of the polymer remain constant, although residual thermal stresses are likely to develop.

Modeling the combined thermal and cure problem can be assisted through some simplifying assumptions. First, the thermal solution can be assumed to be independent of the cure or mechanical solution, so that the thermal problem can be solved independently before the other solutions. The cure kinetics can also usually be assumed to be independent of the stress state of the part, so that the cure problem can be solved based on the thermal problem, and before the mechanical problem.

Flow effects in wound composites can be modeled using Darcy's formula. These calculations may predict gradients in fiber volume fraction through the thickness of the part.

The stress problem is solved most completely when cure shrinkage, thermal shrinkage, thermal gradients, cure gradients, and viscoelastic properties, are all explicitly modeled. Since such a full model is difficult to pose and solve, a number of simplifying assumptions are often made. The

cure kinetics and relaxation properties of the polymer in the composite are assumed to be identical to those of the neat polymer. Linear viscoelasticity, with time-temperature superposition, are applied to simplify modeling of viscoelastic effects. The CTEs of the phases are assumed to be independent of stress state, temperature, and cure history. In some cases, it is adequate to model the viscoelastic properties of the composite only in the cross-fiber direction since, in the fiber direction, properties are largely dominated by the fiber phase.

The authors also mention methods of reducing the likelihood of flaw formation during processing of wound composites. Some of the unique methods they mention are z-direction weaving or reinforcement, to increase interlaminar strength, and using a directed magnetic field to preferentially orient the polymer molecules normal to the fiber direction (this approach is not likely to work).

Blagonadezhin et al. (*6*) provide a review of process modeling, experimental methods, and manufacturing methods for composites, including an extensive list of references. The paper can be roughly organized as follows: analytical predictions of residual stresses in composites; experimental methods for characterizing cure and viscoelastic properties; experimental methods for measuring residual stresses; practical methods for reducing residual stresses; manufacturing approaches for composites; and numerical methods for modeling filling/flow processes during composites manufacturing.

The review of Blagonadezhin et al. presents very little significantly new or novel results. It is worth mentioning that the Sachs and Davidenkov methods are discussed, and the authors mention that theories are being developed which would allow application of these methods to parts of arbitrary geometry.

3. Experimental Measurement of Residual Stresses in Wound Composite Parts

Portnov et al. (*7*) provide one of the earliest complete measurements of residual stresses in wound composite articles. The measurements are made using the Sachs method for hollow cylinders. In this approach, a strain gage is attached to the inside surface of a relatively short (in the axial direction) cross section of the hollow composite cylinder. Strain on the inner surface is then measured as the cylinder is progressively "unwound" from the outside, typically using a rotating sample mount and radially-translating blade. The resulting strain response on the inner surface can be directly related to the residual stress profile thru the thickness of the part. Typically, unwinding is performed from the outside in, with the strain gage on the inner surface, and from the inside out, with the strain gage on the outer surface. The results are then superimposed to get the full stress profile. Hoop and radial stresses can be measured using this

method. The authors provide the equations used to interpret the measurements made using Sachs' method, which assumes an orthotropic elastic material.

The results demonstrate the typical residual stress profile in wound composites. The radial stress is zero at the inner and outer wall surfaces, and tensile within the wall, with a peak somewhere near the center of the wall. The hoop stresses are tensile at the inner surface, and compressive at the outer surface. Rings with thicker walls produce greater residual stresses.

The effect of winding tension is also studied. An increase in winding tension, with tension constant during winding, can produce significantly larger residual stress values than for low-tension winding cases, although the qualitative nature of the stress distributions does not change. Up to a 4× increase in peak stress level is demonstrated by increasing winding tension. Varying the winding tension during winding, in contrast, can produce sizeable changes in the residual stress profile. In the example given, winding tension is increased linearly from the inside of the mandrel to the outside (the winding tension is 6× higher at the outside as compared to the inside). The resulting radial stress profile is similar to the constant tension winding cases. However, the tensile hoop stress at the inner surface is much smaller than in the constant winding tension cases.

Blagonadezhin et al. (*8*) measure residual hoop stresses in very thick (1.5-in wall thickness, 6-in diameter) hollow composite cylinders. Their measurements are performed using the Davidenkov method for hollow cylinders. In this approach, radially-thin hoops of material are removed from cross-sectional slices, and then cut radially. The resulting hoop deflection is used to calculate the hoop stresses at that radial position. Results are given for stress levels at the inner surface and at the outer surface. Experiments are performed for various wall thicknesses and cure temperatures. The results are compared with a simple orthotropic elastic thermal stress model.

The results show that hoop stresses are tensile on the inner surface and compressive on the outer surface. In general, thicker walls and higher cure temperatures produced higher residual stress levels. At the highest cure temperature, however, residual stress levels increased with wall thickness only up to a certain point, and then remained constant (or, in some cases, even decreased). This result is likely due to internal damage, probably matrix cracking. The formation of these flaws serves to relieve residual stresses, preventing stress levels from exceeding some strength value in the composite (most likely interlaminar strength).

In addition to the Sachs and Davidenkov methods, Vinogradov (*4*) provides an extensive list of possible approaches for characterizing residual stress levels in composites.

4. Cure Shrinkage of Neat Polymers

A fundamental understanding of the development of residual stresses and their induced flaws requires an understanding of the effects of cure shrinkage. In section 4.1, an experimental study on cure shrinkage effects in neat polymers is presented. In section 4.2, a series of papers deriving a theory of frontal solidification in polymers, and the corresponding residual stress fields, is presented.

4.1 Experimental Investigations

Korotkov et al. (*9*) provide an interesting study of flaw formation due to cure shrinkage in constrained polymers. The authors propose that, while many flaws formed during processing of composites may be due to residual thermal stresses, chemical strains associated with the cure of the polymer may also produce flaws. This possibility exists because, although chemical shrinkage stresses are generally lower than thermal stresses, the failure strength of the polymer during cure is typically much lower than that of the fully-cured composite. The authors do not specify whether their results are more applicable to macroscale flaws or microscale flaws.

For their first experiment, epoxy resin is cured in glass tubes. Three boundary conditions are imposed by modifying the inner wall of the tube: no adherence to the tube wall (thin, free polyethylene film layer), partial adherence to the tube wall (release agent), and full adherence to the wall (no modification). As expected, the measured extent of polymer shrinkage decreases with increasing wall adherence, due to the constraining effect of the wall.

In a second set of experiments, flaw development is observed during cure of the epoxy in glass tubes. Experiments are first performed under conditions of good wall adhesion, and poor wall adhesion. For the case of good wall adhesion, cohesive failure occurs within the polymer, forming cracks oriented primarily normal to the axis of the tube. For the case of poor wall adhesion, shrinkage is accommodated through failure of the adhesive-to-wall bond, and subsequent wall slip.

Experiments were also performed at low, moderate, and high temperatures. In all cases, wall adhesion was good. During high-temperature cure, shrinkage early in the cure process caused the formation of small voids. These voids grow as cure progresses. This void growth is followed by the formation of cohesive cracks (normal to the axis of the tube). As cure continues, more cohesive cracks form, and existing cracks widen as the crack faces separate. Once a certain density of cracks is reached, no more new cracks are formed, and shrinkage is accommodated solely by the widening of existing cracks.

During low-temperature cure, some small voids may appear. However, the more predominant flaws are “zig-zag” cracks, which extend many diameters along the length of the tube and

wander between the tube walls. Some cohesive flaws may form later in the cure process. Unlike the cohesive flaws, the zig-zag cracks have very smooth crack faces.

During intermediate temperature cure, mostly cohesive flaws form, although their number and severity are less than those observed during high-temperature cure.

The authors propose the following explanations for flaw development. They distinguish between vitrification and gel formation during cure. Vitrification is a dramatic increase in polymer viscosity or stiffness as the sample temperature becomes less than its instantaneous T_g. This transition in viscoelastic properties is due to a reduction in chain mobility, independent of degree of network formation. Vitrification can result from cooling the material below its T_g, or through an increase in the polymer's T_g as it cures. Gelation is the process of network development due to cure, in which the polymer increases in stiffness and becomes a solid. The authors define T_g^{gel} as the temperature at which gelation and vitrification occur simultaneously, which separates high and low-temperature curing regimes.

During high-temperature cure ($T >> T_g^{gel}$), gelation occurs before vitrification. The polymer becomes a solid early in the cure process, so that shrinkage is accommodated by fracture. During low-temperature cure ($T << T_g^{gel}$), vitrification occurs before gelation. The vitrified fluid is relatively easy to cleave, which allows the long zig-zag cracks to form. At intermediate cure temperatures ($T \sim T_g^{gel}$), a simultaneous gelation and vitrification leads to a mixture of failure processes.

Experimental data is compiled to determine the epoxy cure chemistry and cure temperature which forms the least number of flaws. The results show that intermediate temperature cures produce the least flaws, although the reduction relative to low- and high-temperature cure is not striking. Cure chemistry does not produce a measurable change in flaw density.

4.2 Frontal Solidification Theory

A number of authors (*10–16*) provide calculations for residual stress formation due to the frontal solidification of a liquid, where solidification is typically accompanied by a change in volume. The models are presented in a general framework so that they can be applied to a wide range of fields, including metal solidification, geology, and cure of neat polymers. Solutions are presented for a number of geometries, including spheres, solid cylinders, and hollow cylinders, although only the hollow cylinder solutions have direct applicability to wound composites.

Turusov et al. (*10*) studies the frontal solidification of a sphere, with the front traveling from the center of the sphere outward. Shrinkage occurs during solidification. The general stress state can be explained qualitatively by envisioning the solidification of a layer of liquid immediately surrounding an existing solid core. The shrinkage of the liquid layer during solidification puts a compressive radial and hoop stress on the existing solid core. The now-solidified liquid layer undergoes radial compression, and hoop tension. The superposition of these stress fields over many layers of material leads to the final stress state.

Calculations are presented for solid and hollow spheres. The analytical solution models the liquid phase as perfectly viscous, with a sudden transformation to a perfectly elastic solid. The model can accommodate shrinkage or expansion upon solidification. Solidification is assumed to occur in an infinite bath of fluid.

For solidification of a solid sphere, radial stresses are compressive at the center (and possibly infinite) and decay to zero at the outer surface. Hoop stresses are compressive at the center and become tensile at the outside of the sphere. For hollow spheres, the hoop stresses are similar to the solid sphere. However, the radial stresses are necessarily zero at both inner and outer wall surfaces, so the compressive radial stress shows an extremum within the sphere wall.

Klychnikov et al. (*11*) model the frontal solidification of a solid cylinder, with the solidification front moving from the center of the cylinder outward. In addition to cure shrinkage, the model can accommodate nonuniform temperature distributions and thermal-expansion stresses. Since the model is perfectly elastic, separate stress field solutions are presented for the effect of shrinkage and thermal expansion, which can be superimposed for the complete solution.

Unfortunately, only limited calculations are presented. For a hollow cylinder, the results are similar to the hollow sphere. Radial stresses are compressive and equal to zero at the cylinder wall surfaces, with an extremum within the wall. Hoop stresses are compressive at the inner surface and tensile at the outer surface. Axial stresses are similar to hoop stresses, compressive at the inner surface, and tensile at the outer surface.

Turusov et al. (*12*) present the solution for frontal solidification of a sphere, where the front travels from the outside of the sphere inward. One interesting application of this solution is planet solidification. The solid phase is elastic, and the liquid phase is viscous and perfectly incompressible. Separate shrinkage coefficients are provided for the liquid and solid phases, to handle more complex solidification characteristics, although the solidification front is still assumed to be very sharp. In addition to the usual stress field solution within the solidified region of the sphere, the pressure developed within the liquid is given by the radial stress on the inner surface of the sphere.

Three cases are studied: equal shrinkage in the solid and liquid phases, more shrinkage in the solid phase than in the liquid phase, and liquid-phase expansion with solid-phase contraction. For the case of equal shrinkage, the pressure in the fluid increases slightly early in the solidification process, but then rapidly becomes negative as solidification progresses. This behavior is caused by the shrinkage of the sphere wall during solidification, which tends to hydrostatically tension the trapped fluid inside. The authors predict that this pressure drop would likely cause void formation within the fluid during many solidification processes. The hoop stress on the outside of the wall is tensile early in the process, but becomes compressive as the solidification front progresses inward. Unfortunately, the authors do not provide the final residual-stress distributions for the spheres.

In the case of more solid-phase shrinkage than liquid-phase shrinkage, stress histories are similar to the first case, with smaller final stress values. In the case of liquid expansion with solid contraction (solid contraction greater than liquid expansion), the liquid pressure increases as solidification progresses. The hoop stress on the outside wall remains tensile throughout the solidification process.

Turusov and Metlov (*13*) present the case of solidification of an orthotropic elastic hollow cylinder, with the solidification front moving from the outside to the inside of the cylinder. This calculation is intended to represent the physics of frontal solidification during cure of wound composite cylinders. A number of boundary conditions are presented, including the effect of mandrel constraint on the inner wall.

The calculations show that, similar to the outside-in solidification of the sphere, negative pressures can develop within the liquid phase. The radial stresses are generally tensile, equal to zero at the outer surface (free boundary) and at a maximum at the inner surface (constrained by the mandrel). The hoop stresses are compressive on the outer surface and tensile on the inner surface.

Metlov and Turusov (*14*) present an extensive derivation of the frontal solidification problem. The solution is formulated as a boundary value problem, so that it can be applied to solidification of a body of arbitrary geometry. The formulation is also capable of handling viscoelastic and relaxation behaviors. Specific solutions are provided for an isotropic hollow elastic sphere, an isotropic solid elastic sphere, and a hollow isotropic cylinder with relaxation. No numerical calculations are provided.

Metlov and Turusov (*15*) present the solution for the frontal solidification of two nearby solid cylinders in an infinite bath of fluid, with solidification originating at the center of each cylinder. The solidification shrinkage, in addition to creating a residual stress state within the solidified bodies, also attracts the two solidification centers. This attraction is due to the low-pressure field which develops between the two bodies, which arises from the constant requirement for liquid flow towards the cylinders in order to accommodate their progressive shrinkage.

All of the papers quoted so far in this section appeared in the Soviet literature only. A summary of these theories, Turusov and Metlov (*16*), was published in the journal *Polymer Science* in 1994. In addition to formulating the frontal solidification solution in very general terms, many of the earlier specific calculations are also republished.

5. Residual Microstress Development

5.1 Thermal Microstresses in Thermoplastic Composites

Andreeva et al. (*17*) study residual microstress development in fiber-reinforced thermoplastics. Their application of concern is short glass, fiber-reinforced polyethylene, which is proposed as a low-friction bearing surface. The authors are interested in determining if the microstresses developed during a specific thermal cycling history, associated with a rotating bearing application, are sufficient to cause property degradation in the composite.

A simple linear elastic model of thermal residual stress development is presented, and example calculations performed for various polyethylene composite systems. The calculations, although conservative, indicate that thermal microstresses may be sufficient to cause fiber-matrix debonding.

As a complement to the theoretical calculations, a model system using millimeter-sized glass and steel particles in a polyethylene matrix were fabricated. The experimental systems were processed to be stress-free at room temperature. A grid was etched onto the sample surface to aid in strain visualization.

Heating the model systems showed that the reinforcing phases, whose CTE is significantly less than that of polyethylene, restrained the polyethylene from freely expanding. A number of example experiments are shown, including cylindrical and spherical particles, and the effect of multiple particles. Cylindrical particles are shown to be more effective than spherical particles for constraining thermal expansion, while increasing the volume fraction of particles increases the overall level of thermal constraint.

5.2 Thermal and Chemical Microstresses in Thermoset Composites

Abibov and Molodtsov (*18*) study the development of microstresses in thermosetting composites using photoelastic measurements on a model system. The model system consists of 10-mm diameter rods cast in epoxy, which is cured at elevated temperatures. They first examine the residual stress field for two systems: one reinforced with a single aluminum (Al) fiber, and one reinforced with a single, precured rod of epoxy, identical to the epoxy used as the matrix material. Since the epoxy rod has the same CTE as the cured matrix, the latter experiment isolates the effect of chemical shrinkage. The resulting residual stress field for the epoxy rod specimen is much lower than that for the Al rod specimen, showing that chemical residual stresses for this material system are negligible compared to thermal residual stresses. The authors also present stress-field measurements for two and four interacting fibers, with varying spacing.

In a follow-on study, Molodtsov (*19*) presents a linear elastic model for the development of thermal microstresses in reinforced systems. Calculations are performed for infinitely periodic hexagonal and cubic arrangements of solid cylinders at various volume fractions. In general, higher volume fractions leads to higher levels of residual stress, since tighter fiber packing implies smaller resin gaps between fibers. The theoretical calculations match reasonably well with the experimental measurements of Molodtsov's previous study (*18*).

Sarabeev and Perlin (*20*) also perform photoelastic measurements of residual stresses in model composite systems. Their model systems consist of 6-mm diameter glass rods in epoxy and polyester resins. In all cases, four fibers are arranged in a hexagonal packing arrangement, with a spacing corresponding to a fiber volume fraction of 70% (for an infinitely periodic system). The resins are cured at moderate or high temperatures, and then cooled to room temperature. The photoelastic method used in this study enables measurement of the full 3-D stress field in the matrix, including the shear stresses at the fiber-matrix interface. Damage in the form of cracking is also apparent in many samples.

The results show that the largest tensile stresses which occur in the matrix phase occur in the thin regions between fibers, which consequently are also the most likely location of matrix cracking. The shear stresses are generally greatest at the fiber matrix interphase. However, their results show that slightly higher shear stresses are possible outside of the unit cell, roughly one radius away from the fiber. This result may indicate that shear failure is more likely to initiate near the resin-rich surfaces of parts, than within the bulk of a composite. In all cases, the fibers are in radial compression at the fiber-matrix interface.

Surprisingly, the model system measurements show higher residual stress levels for low-temperature cured systems, as compared with high-temperature cured systems. Since higher cure temperature would be expected to lead to higher residual stress levels, more subtle cure effects, relaxation, or matrix microdamage may be occurring. Another interesting result is that the compressive stresses at the fiber-matrix interface are significantly higher in the epoxy system, as compared with the polyester system. The authors claim that this increased compressive stress improves fiber-matrix bonding, and directly contributes to the superior performance of epoxy composites as compared to polyester composites.

In a follow-on study, Sarabeev and Perlin (*21*) repeat their earlier model experiments, but this time show the effect of coupling agents (fiber coatings) on residual microstress development. They show remarkable changes in residual stress levels (increase by as much as 115% or decrease by as much as 80%) depending on the type of coupling agent used.

Korotkov and Rozenberg (*22*) model chemical shrinkage-induced microstresses in composites by analyzing curing under constrained conditions for various unit-cell geometries. Their model assumes square packing of octagonal fibers separated by uncured polymer matrix, with the effect of fiber volume fraction analyzed by adjusting the spacing between fibers. The problem is solved using a boundary value approach, and assuming linear elastic constitutive behaviors for

both the fiber and matrix phases. The results show that chemical shrinkage stresses are significant, and may induce microdamage, at very high-fiber volume fractions.

6. Modeling Residual Macrostress Development

The earliest literature on residual macrostress modeling for filament-wound composites followed two main approaches: one rooted in classical continuum theory of anisotropic elasticity and the other deriving from statistical mechanics for two-phase systems. Statistical theories were soon surpassed by continued development of continuum elasticity models, whose sophistication and accuracy greatly increased through incorporation of viscoelastic relaxation effects. These models were further refined through the incorporation of nonuniform material properties, cure kinetics, and cure shrinkage.

6.1 Continuum Elastic Models

Bolotin and Bolotina (*23*) propose a method for the analysis of residual stresses in filament wound composites by subdividing the model into five stages: winding, heating, polymerization, cooling, and removal from the mandrel. The initial stresses that develop during winding are superimposed with the subsequent stress increment during the heating stage. Polymerization is treated as a process during which the mechanical and thermophysical properties of the material change. Subsequently, the fully cured product is modeled as a thick-walled anisotropic hollow cylinder in contact with an isotropic solid cylinder or hollow cylindrical mandrel. Elastic theory is used throughout and several simplifying assumptions are made. Their results show that if the initial tension during winding is sufficiently small, the residual stresses in the cylinder are chiefly determined by the thermal shrinkage during cool down. The difference between the cure temperature and the temperature at which the cylinder releases from the mandrel is proportional to the initial pressure on the mandrel (from winding).

Biderman et al. (*24*) also analyze the development of residual stresses in filament-wound cylinders through elastic superposition of the results from the five stages of fabrication. The results and conclusions of this study are very similar to those of Bolotin and Bolotina (*23*).

Portnov et al. (*25*) address the issue of nonuniformity in material properties and their effect on thermal stresses in filament-wound articles. Such nonuniformity can arise from variation in resin content, variable tension during winding, and other effects. They assume that the stiffness and CTE vary linearly across the thickness of an anisotropic hollow cylinder and solve the elastic boundary value problem. Their results show that the effect of the radial stiffness variation is slight for all cases analyzed. By varying the fiber volume fraction from 0.35 to 0.5, the range typically obtained for glass-reinforced cylinders, their analysis shows that the effect of nonuniform resin content was not very great.

Tikhonov (*26*) models unidirectional composites using elastic stress potentials, and explicitly accounts for the anisotropic elastic and thermal expansion properties of the reinforcing fibers (e.g., carbon fibers). These fiber anisotropy effects become most important at high fiber volume fractions. Neglecting fiber anisotropy leads to an underestimation of the circumferential stresses and exaggeration of the absolute value of the radial stresses.

6.2 Statistically-Based Elastic Models

Volkov and Mendelson (*27*) propose a model for estimating the residual thermal stresses induced during uniform cooling of a randomly reinforced plastic material. The problem is formulated through a statistically-based elasticity theory, which takes the form of a boundary value problem solved using Green's functions. This model is extended by Volkov (*28*) to incorporate chemical shrinkage of the resin.

Stavrov and Velichko (*29*) also use a statistical elasticity approach to calculate the average stresses arising from thermal and chemical shrinkage in reinforced polymers. They define the boundary value problem of a two-phase system and employ the Green's function method to solve the problem. Both unidirectional fiber-reinforced composites and randomly filled polymers were considered. In the latter case, the average shrinkage stress is compressive in the reinforcement and tensile in the matrix. These results lead to the conclusion of a positive correlation between shrinkage of the matrix and a decrease in the compressive strength of the composite.

6.3 Viscoelastic Models

Bolotin and Vorontsov (*30*) apply linear viscoelasticity to investigate the residual stress development in filament-wound cylinders with particular attention to incorporating a temperature-dependent strength analysis of the material based on other experimental work. Only radial relaxation was accounted for in the material description. Their results indicate that the contribution of chemical shrinkage to the final residual stress was less than a few percent in all cases analyzed. The rate of stress development during cool down is closely coupled to the rate of cooling. Under certain cases of rapid cooling, they find that the radial stresses may exceed the transverse strength and lead to microcracking of the cylinder.

Afanasev et al. (*31*) study the temperature fields and thermal stresses in filament-wound composites subjected to nonuniform cooling using a nonisothermal, viscoelastic analysis. They assume thermorheological simplicity, employing time-temperature superposition, and treat the matrix phase as a simple Maxwell fluid. The problem is solved using a finite difference technique. The solutions they present specifically address the influence of cooling rate and spatial thermal gradients on stress development during processing, and residual stress state. They note that incorporation of viscoelastic effects can have a significant bearing on the instantaneous stress states, especially for thick-walled cylinders.

Korotkov et al. (*32*) examine the effect of temperature dependence of the material properties on the thermal stresses in solid polymer cylinders, hollow polymer cylinders, and thick-walled,

hollow composite cylinders. The polymer phases are modeled using a nonlinear generalized Maxwell equation, retaining two terms of the relaxation spectrum, and temperature variations in time and space are included. Their results indicate that the thermal stresses and their variations with temperature are closely coupled to the rate of change of temperature in the glassy state, and are nearly independent of the rate in the rubbery phase. The special role of the glass transition region in thermal stress analysis is found to be important. The rate at which this region is passed determines the subsequent value of the thermal stresses and their relaxation process.

The analysis for the composite cylinder in Korotkov et al. (*32*) is brief. In a subsequent study, Korotkov et al. (*33*) perform a more complete analysis of the thermal stresses generated in an orthotropic, viscoelastic, hollow composite cylinder. The matrix phase is again modeled using a nonlinear generalized Maxwell equation, retaining two terms of the relaxation spectrum. The temperature field in the cylinder varies in both time and space. A numerical solution is obtained using typical values for glass/epoxy composites. They investigate the effect of cooling rate and relative thickness of the composite on the relaxation process. For cylinders above a certain critical thickness, the relaxation process leads to a reduction in the radial residual stresses, which improves with slower cooling rates. Yet, for cylinders below this critical thickness, the relaxation process leads to an increase in radial stresses above those predicted by elastic analysis alone.

Korotkov et al. (*34*) further refine their model by incorporating chemical shrinkage, which was assumed to be proportional to the heat liberated during cure. They assume a long hollow cylinder (axisymmetric) of an anisotropic viscoelastic material and solve the general problem of thermoviscoelasticity. Temperature fields vary spatially and temporally, and the problem is solved using a finite difference technique. Their results show that for thick composite cylinders, radial tensile stresses can be generated prior to full cure. Even small levels of tensile stresses at or near matrix gelation can lead to microcracking and attendant loss in mechanical integrity.

All of the previously cited viscoelastic models in this section treat only the stresses that are generated due to thermal, cure, and relaxation effects. These models do not directly incorporate the effects of winding tension. In contrast, Bolotin et al. (*35*) formulate a complete model of the residual stress problem in filament winding, starting from the moment the first layer is wound and finishing with the removal of the finished article from the mandrel. Their approach subdivides the winding process into a series of stages, each analyzed separately, where the results from the previous stage are used as initial conditions for the following stage. Winding tension and resin-filtration effects are explicitly modeled.

They begin with a rigorous description of the consolidation process during winding while making allowance for motion of the fibers through the resin, which can result in fiber-resin segregation and relaxation of stresses. In the next stage, the heating and polymerization of the resin are considered while allowing for the build up in resin mechanical stiffness and cure shrinkage. In the final stage of analysis, the composite is assumed to be fully cured and modeled

using a standard viscoelastic description of material properties. Numerical solutions are generated using an implicit, finite-difference scheme. One of the main conclusions of their study is that fiber motion and segregation during winding leads to lower radial tensile stresses. Thus, when the radial strength is small the effects of fiber motion must be considered especially for "power" winding methods in which the filament tension is high during the winding process.

7. Methods of Controlling Residual Macrostresses in Wound Composites

Since a major motivation for studying residual stress effects in composites is to prevent the formation of flaws or other performance deficiencies, a number of experimental and theoretical studies have proposed specific measures for reducing or controlling residual stress effects.

7.1 Winding Tension

Tarnopol'skii and Portnov (*36*) propose to vary winding tension during the winding process in order to control the final distribution of hoop stresses in the part. They construct a model assuming orthotropic, linear elastic behavior, with separate high-temperature and low-temperature radial moduli. Only the radial modulus varies with temperature, since it is a matrix-dominated property. The prestresses in each layer of material are proportional to the winding tension, and the cumulative effect of the addition of many layers determines the final stress state in the material.

Under conditions of constant winding tension, the authors show that the hoop stress will be at a minimum at the cylinder's inner and outer wall surfaces, and exhibit a maximum within the cylinder walls. All stresses are tensile. They then formulate the inverse problem, so that a winding tension history can be calculated to give a prescribed final residual stress profile. They provide example solutions for uniform stress after winding, uniform stress after removal from the mandrel, and uniform stress after removal from the mandrel, with inclusion of the effect of thermal strains. Unfortunately, calculations showing the effect of winding tension on radial stresses are not given.

Nikolaev and Indenbaum (*37*) use the model of Bolotin and Bolotina (*23*), an elastic superposition model assuming uniform temperature and curing fields, to investigate the residual stresses in filament-wound glass-reinforced polymers. In particular, they concentrate on various controlled winding tension regimes and their effects on final residual stress state. Their model predicts that winding processes that employ a linear ramp in winding tension lead to greater radial compression near the outer surface and an overall reduction in tensile residual stresses. Through correlation with experimental data, the authors also find that residual stresses can be most effectively reduced by preheating the tow and mandrel prior to winding.

7.2 Winding Angle

Beil et al. (*38*) proposed to vary winding angle during the winding process in order to control the final residual stress distribution. Their model is based on the principle that, for an anisotropic elastic hollow cylinder, thermal stresses cannot develop if the hoop and radial CTEs obey the relationship

$$\mathrm{CTE}_r = \frac{\partial}{\partial r}\left(r \cdot \mathrm{CTE}_\theta\right). \tag{1}$$

Using this relationship, as well as standard orthotropic formulations relating fiber orientation to bulk CTEs, they are able to formulate the inverse problem for calculating the required fiber orientation as a function of radius which gives the desired residual stress behavior.

The results show that the desired quasi-isotropic CTE behavior is only possible if the wind angle is very shallow, so that there is very little hoop-direction reinforcement. Under this condition, the composite tends toward a uniaxial hollow composite cylinder, with very similar radial and hoop-direction moduli. This result shows that the concept of varying winding angle to get zero residual stress is probably not practical, since in most cases significant hoop direction reinforcement is needed to achieve the required final mechanical properties in the part. In addition, the wind angle is typically designed to produce specific mechanical properties, and is not a free variable to be altered to meet residual stress requirements.

7.3 Winding Speed and Temperature

Korotkov et al. (*39*) propose to vary winding speed and temperature in order to influence the relative degrees of cure of each layer in the wound composite article. Their goal is to eliminate or minimize the radial tensile stresses associated with shrinkage of the polymer during cure, which has been proposed as a major source of voids and delamination flaws in thick-walled composites. The general approach is based on the concept that if a wound composite is cured in bulk, then the cumulative effect of shrinkage and constraint of all the layers leads to significant radial tensile stresses, with the maximum stress near the midplane of the wall. In contrast, if the composite is built up layer-by-layer, so that each layer is fully cured before the addition of the next layer, then residual shrinkage stresses are minimized.

The model used is a two-stage model, with a simple kinetic equation for degree of cure x, and shrinkage strain linearly proportional to x. The polymer phase is modeled as a viscous liquid up to a critical conversion x^*, and modeled as an elastic solid for all conversions greater than x^*. The winding temperature alters the initial degree of cure for the resin, since it is assumed that some cure occurs before the heated resin reaches the mandrel, and determines the rate of cure once the resin is placed on the mandrel. Heat conduction between layers is not considered, although the resulting temperature distribution is monotonic enough so that the results are not grossly inaccurate. The winding rate is also varied, which alters the cure time per layer before addition of the next layer, therefore changing the degree of cure as a function of time and layer

number. Decreasing the winding rate has a similar effect as increasing the cure temperature, since both effects increase the degree of cure per layer.

The authors show that, as winding rates are reduced, the residual stress levels approach those of a layer-by-layer cured composite.

In a subsequent paper, Korotkov et al. (*40*) modify the model slightly, so that instead of varying winding temperature and rate, there is a prescribed heat flux on the inner and outer wall surfaces, as well as variable winding rate. In this case, higher heat fluxes cause each layer to cure faster before addition of the next layer. Slower winding rates are equivalent to higher heat fluxes. Chemical and thermal shrinkage are accounted for, although radial stresses are only calculated during cure and not during subsequent cooling. The chemical shrinkage model is also modified so that the shrinkage does not initiate until $x > x^*$.

The results show that altering the heat flux on the inner wall surface is largely ineffective at altering the final residual stress profile, which is expected since new layers of material are added to the outside of the cylinder rather than the inside. Varying the heat flux on the outer surface proves very effective at reducing residual stress levels, although at high winding rates the required cure temperatures necessary to achieve rapid curing are impractically high and would, in fact, thermally degrade the composite.

While the concept of layer-by-layer curing appears beneficial theoretically, the authors do not acknowledge that the final mechanical properties of the composite could suffer. The polymer matrix in the composite will only achieve its full mechanical performance if it is allowed to form as a homogenous, continuously networked material. By curing layer-by-layer, even partially, the network formation between layers could be reduced. In fact, the most likely effect is that the interlaminar strength of the composite will decrease, so that interlaminar failure during subsequent cooling is more likely to occur.

An interesting alternative approach, which is not explored by the authors, would be to vary curing rate during winding, by using a catalyzed system and continuously varying the concentration of catalyst as winding progresses. The concentration of catalyst could be decreased with increasing layer number, so that, under subsequent isothermal conditions, the composite would effectively cure layer-by-layer from the inside towards the outside. The advantage of this approach is that a full interpenetrating network would be formed, so that mechanical properties of the final composite would not suffer. It is not clear whether this approach is practical, or whether diffusion of the catalyst would prevent any meaningful homogeneity through the wall thickness.

7.4 Bulk Cure Temperature

Bakharev and Mirkin (*41*) use a thermoelastic analysis to study the effect of thermal history on cure and residual stress development in filament-wound articles. Their results suggest that residual stresses can be decreased by performing an initial cure at a relatively low temperature,

followed by final curing at a higher temperature. The precure increases polymer network formation at low temperatures, which decreases the total thermal residual stresses generated upon cool-down from the second, higher-temperature dwell.

Turusov et al. (*42*) begin by discussing the difference between flaws formed during cooling, vs. flaws formed during cure. They present experimental results for two thick-wound hollow composite cylinders, both glass fiber/epoxy composites, but with different resin systems. Under nominal conditions, both cylinders exhibited interlaminar flaws. To reduce thermal stresses during cooling, a second set of cylinders was cooled very slowly. This approach only serves to eliminate thermal gradients through the thickness, so that residual stresses during cooling are reduced, but final residual stresses are identical to those produced by rapid cooling. Under slow cooling, the composite with the “EDT” resin system no longer produced interlaminar flaws, but the composite with the “EKR” resin system still exhibited interlaminar flaws. Further experiments showed that the only significant difference between the resin systems is that the EKR exhibits nearly twice the chemical shrinkage during cure as the EDT. Based on the result, the authors conclude that in the EKR system flaw formation must be occurring due to shrinkage during cure of the polymer phase.

To address this problem, the effect of cure temperature on flaw formation and residual stress development is considered. The authors propose that, if cure is performed at high temperatures, the polymer remains a low-viscosity liquid well into the conversion process. Assuming shrinkage occurs uniformly during the full conversion process (i.e., in both the liquid and solid phases), then shrinkage is likely to produce voids in the polymer. In contrast, if cure occurs at low temperature, then the uncured polymer remains relatively viscous, and converts to a somewhat hardened state at relatively low-conversion levels. Therefore, shrinkage flaws are less likely to occur.

A limitation of low-temperature curing, however, is that full conversion is unlikely to be reached. Therefore, low-temperature curing must be followed by a high-temperature postcure to ensure full mechanical properties of the part.

A further benefit of the low-temperature cure approach is that the hardening of the resin at low temperatures essentially sets the thermal stress-free state at that temperature. The postcure process will actually induce compressive radial stresses, which are relaxed upon cooling to the original cure temperature, and which then become tensile upon cooling to room temperature. The level of these tensile thermal stresses is much lower that the high-temperature cure case, where the stress-free state is set at a significantly higher temperature.

Based on this philosophy, the authors manufacture an EKR composite cylinder using the two-stage thermal cure approach. The resulting cylinder does not exhibit interlaminar flaws.

7.5 Cooling Rate

Korotkov et al. (*43*), Afanasev et al. (*44*), and Dubovitskii et al. (*45*) model the effect of cooling rate on the formation of interlaminar flaws in thick-wound composites. Their approach is based on the assumption that flaw formation is mostly likely to occur at some intermediate temperature during cooling. Although only limited experimental data is available, there appears to be clear evidence that the interlaminar strength of cured thermosetting composites exhibit strong temperature dependence. In general, interlaminar strength decreases with increasing temperature, with the sharpest drop occurring around the T_g of the material. In contrast, thermal stresses develop linearly with temperature, with a zero stress state at high temperatures and reaching a maximum at room temperature. Assuming flaw formation takes place when the thermal stresses exceed the interlaminar strength of the material, flaws are most likely to occur at intermediate temperatures where the thermal stresses are significant, but the interlaminar strength is still relatively low.

With this understanding of flaw formation, the goal of modifying the composite cooling rate is to alter the residual stress conditions during cooling, especially near the T_g of the material. Note that, assuming elastic behavior during thermal stress development, altering cooling rate will only change the calculated residual stress profile during cooling, and will not affect the final calculated residual stress state of the composite under equilibrium at room temperature.

The models in references (*43–45*) are similar. Temperature or heat-flux boundary conditions are applied to the outer and/or inner wall surfaces, and the axisymmetric heat-conduction problem is solved for the resulting thermal profiles as a function of time (or temperature). This result is then used to calculate the residual radial stresses in the composite as a function of temperature, assuming that the composite is orthotropic linear elastic, with constant CTEs in the radial and hoop directions. Superimposed on these results is the measured or estimated interlaminar shear strength of the composite as a function of temperature, with flaw formation predicted to occur if this value is less than the residual tensile stress at any temperature. Korotkov et al. (*43*) and Dubovitskii et al. (*45*) additionally formulate the optimization problem, so that the total cooling time is minimized while avoiding flaw formation.

The results show that, in general, flaw formation during cooling can be suppressed by rapidly cooling the outer surface relative to the inner surface, so that the maximum radial thermal gradient occurs when the midplane of the wall is slightly above the T_g of the polymer. In fact, applying heat to the inner surface, to maintain high thermal gradients during cooling, can also prove beneficial. These surprising results can be explained qualitatively using geometric arguments. When the outer surface is much cooler than the inner surface, the outer surface is fully contracted (minimum circumference), while the inner surface can be considered fully expanded (maximum circumference). These conditions cause an effective reduction in wall thickness, with the formation of compressive radial stresses, or a decrease in the magnitude of

tensile stresses, at the midplane of the wall. This decrease in radial tensile stresses leads to a reduction in the likelihood of interlaminar flaw formation.

Interestingly, this result directly contradicted conventional wisdom at the time, which held that slow cooling (and uniform wall temperatures) was always the best way to minimize residual stresses and flaw formation. By solving for the fastest cooling rates that do not produce flaws, the models show the condition of uniform cooling requires in some cases 5× as long as the corresponding nonuniform cooling case.

The results of reference (*45*) express thickness effects more explicitly. They show that, for thin-walled cylinders, the temperature profile over the wall thickness is usually very uniform, so that fast uniform cooling is always the most efficient approach. For very thick cylinders, the outer surface is typically cooled quickly to room temperature, and then held at that temperature until the temperature equilibrates to a linear profile within the wall. The inner surface is then cooled as rapidly as possible to room temperature. For cylinders of intermediate thickness, the outer surface is often first cooled rapidly, and before it reaches room temperature, rapid cooling is initiated in the inner surface.

7.6 External Pressure

Rabotnov and Ekel'chik (*46*) show that if external pressure can be applied to the cylinder during cooling, flaw formation at elevated temperatures is less likely to occur. The effect of external pressure is to impose compressive stresses in the radial direction, which temporarily offset the tensile stresses developed during cooling. Note that, upon removal of pressure at room temperature, the residual stress level is unchanged from the case of cooling under no pressure.

While the effect of applied pressure is theoretically promising, the author does not provide any guidance on achieving this result in practice. One approach may be to apply vacuum bagging during cooling of the cylinder to room temperature.

7.7 General Optimization Approaches

Afanasev (*47*) and Afanasev and Muravev (*48*) address the process optimization of wound composites in very general terms. Various optimization schemes, solution methods, constraints, and optimization criteria are discussed. Among the possible quantities to be optimized are final residual stress levels, probability of flaw formation, and total process time. The results of methods presented are not specific enough to be of any immediate use for design or fabrication of structures, and many of the optimization discussions may now be obsolete due to improvements in computational resources and prepackaged optimization routines.

7.8 Other Modifications to the Winding Process

7.8.1 Mandrel Material

Ogilko (*49*) uses linear viscoelasticity theory with Rabotnov operators to study the effect of various factors on residual stresses induced by thermal shrinkage. The effect of mandrel material, degree of anisotropy of the composite, and relaxation of the matrix are all considered. Only radial relaxation is allowed while uniform cooling conditions are assumed. Analysis of cross-ply cylinders shows that the magnitude and distribution of thermal stresses in the cylinder depends on the ratio of the longitudinal and transverse layers in the shell, and particularly strongly on the ratio of the reduced thermal expansion coefficient of the shell in the circumferential direction to the thermal expansion coefficient of the mandrel. A sharp decrease in residual stress is noted when, for the same composite parameters, the mandrel material is changed from steel to gypsum.

7.8.2 Axially Expandable Mandrel

Pichugin et al. (*50*) present experimental results for winding on an axially expandable mandrel. The purpose of the expandable mandrel is to allow winding to occur at low-winding tensions, with subsequent tensioning of the completed part prior to cure by lengthening the mandrel. Winding under low tensions allows faster winding than conventional winding, while minimizing fiber damage. Assuming there is at least some axial component to the winding, then lengthening the mandrel causes the wound fibers to become tensioned. This tensioning removes fiber wrinkling, and also allows a prescribed level of prestress to be applied to the part. Since tension can also be continuously varied during cure, stress relaxation associated with resin and fiber flow can be avoided.

Experimental results showed that part density increased with increased mandrel tension, while part thickness (for constant ply count) decreased with increased mandrel tension. Axial stiffness also increased monotonically with mandrel tension, although hoop stiffness was not changed. Hoop strength (burst stress) exhibited an optimal tension value. At low tensions, increasing tension improved fiber straightness, which improves tensile strength and therefore burst strength. Above the optimum conditions, further tensioning only increased prestress in the fibers, which limited the ultimate external hoop stress to failure.

Note that the applicability of this approach is limited by part geometry, and the need to fabricate an expandable mandrel.

7.8.3 Secondary Packing Mandrel

Blagonadezhin and Mezentsev (*51*) present experimental results for winding in which a secondary mandrel (also called a "packing mandrel" or "roller") applies pressure to the part during winding and subsequent cure. The secondary mandrel is presumably mounted parallel to

the primary mandrel so there is constant, uniform contact along one line of the composite part. The mounting allows constant force to be applied to the primary mandrel.

The results show that, in general, mechanical properties improve. Stiffness increases, tensile strengths increase, and void fraction decreases. However, interlaminar strength also drops significantly. This effect is likely due to too low of a resin volume fraction, since the packing mandrel tends to squeeze out a significant portion of the resin.

Note that this approach is generally limited to simple axisymmetric parts, and requires fabrication of a custom secondary mandrel and mounting apparatus.

7.8.4 Stiffeners

Vorontsov (*52*) considers the residual stresses induced during fabrication of ring-stiffened composite shells. In this arrangement, a series of discrete, composite, box-beam ring stiffeners are evenly spaced on the mandrel prior to winding. The composite shell is then wound directly onto the ring stiffeners, and bonds to the stiffeners during cure. A thermoviscoelastic model, with allowance for relaxation during winding and curing, is used to predict residual stresses. The resulting calculations show that careful sizing and positioning of the ring stiffeners, and selection of mandrel material, is necessary to prevent failure at the stiffener-to-shell interface during processing.

7.8.5 Hybrid Composites

Blagonadezhin et al. (*53*) describes the manufacturing of three-layer hybrid wound composites, using a mixture of glass fiber (G) and carbon fiber (C) plies. Four material architectures are investigated: GGG, CCC, GCG, and CGC. For the glass fiber layers, some pretension variation is also tried, while the brittleness of the carbon fiber layers limits them to only low-winding tensions. Residual stress levels are directly measured using the Sachs method and compared with theoretical predictions.

The results show that varying material architecture can produce some qualitative changes in the residual stress profile, although the changes are not significant or necessarily beneficial. Varying winding tension produces only minor effects on the stress profiles.

Indenbaum (*54*) formulates a solution for a more general "hybrid" wound composite, with multiple material layers of arbitrary mechanical properties (static elastic properties and CTE). A finite difference, thermoelastic solution is presented with continuity enforced between layers. The approach is similar to, albeit more complicated than, standard theories of laminated shells. The results indicate that, for the specific material properties considered, the maximum residual stresses do not depend significantly on the number or sequence of layers.

8. Papers Not Reviewed

For completeness, we give brief summaries of papers which were included in the original group of Soviet/Russian papers, but which have not been included in this review.

Malyshev and Salganik (*55*) discuss the differences in crack sensitivity of lap-shear and butt adhesive joints. This article was not considered relevant to the topic of residual stress development in composites.

References (*56–64*) were only available in Russian, and were not reviewed.

9. References

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